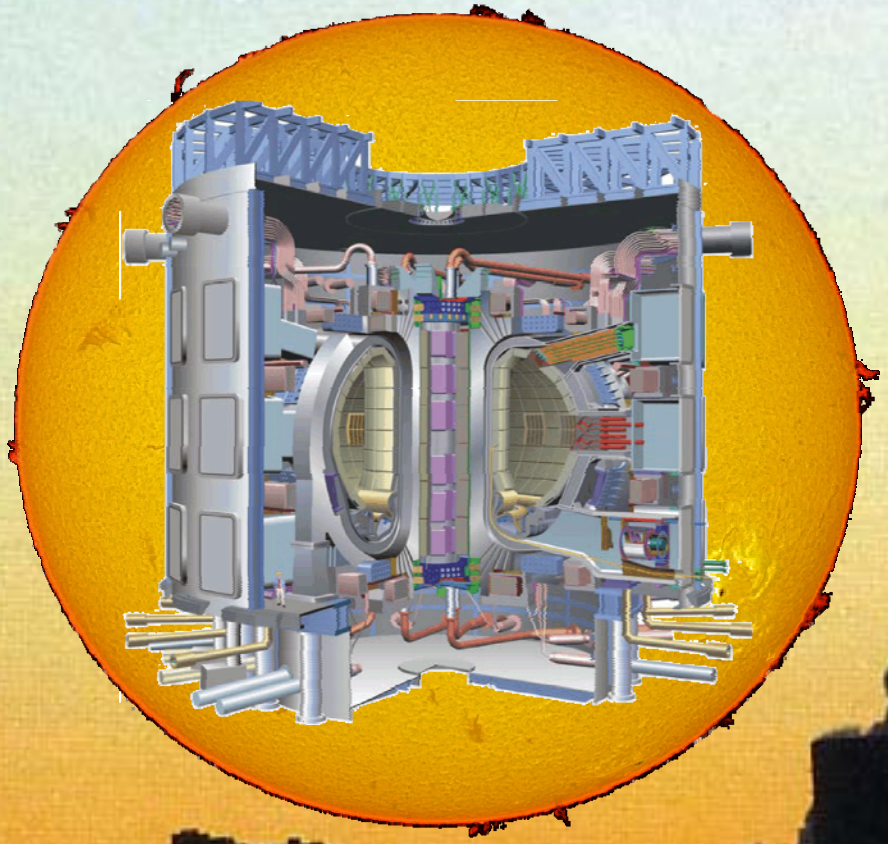
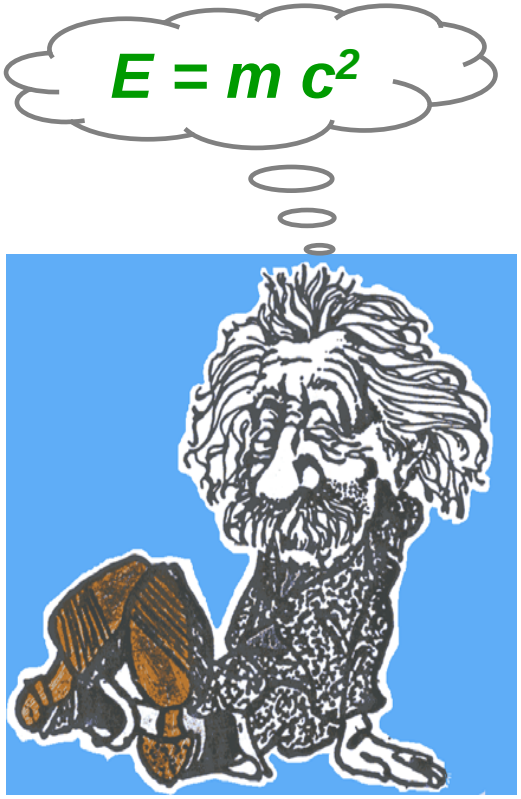
ITER* : la fusion, mode d'emploi…



* ***I**nternational **T**hermonuclear **E**xperimental **R**eactor*

Quelle masse de matière faut-il mettre en jeu pour échanger une quantité d'énergie de **1 kWh** ?

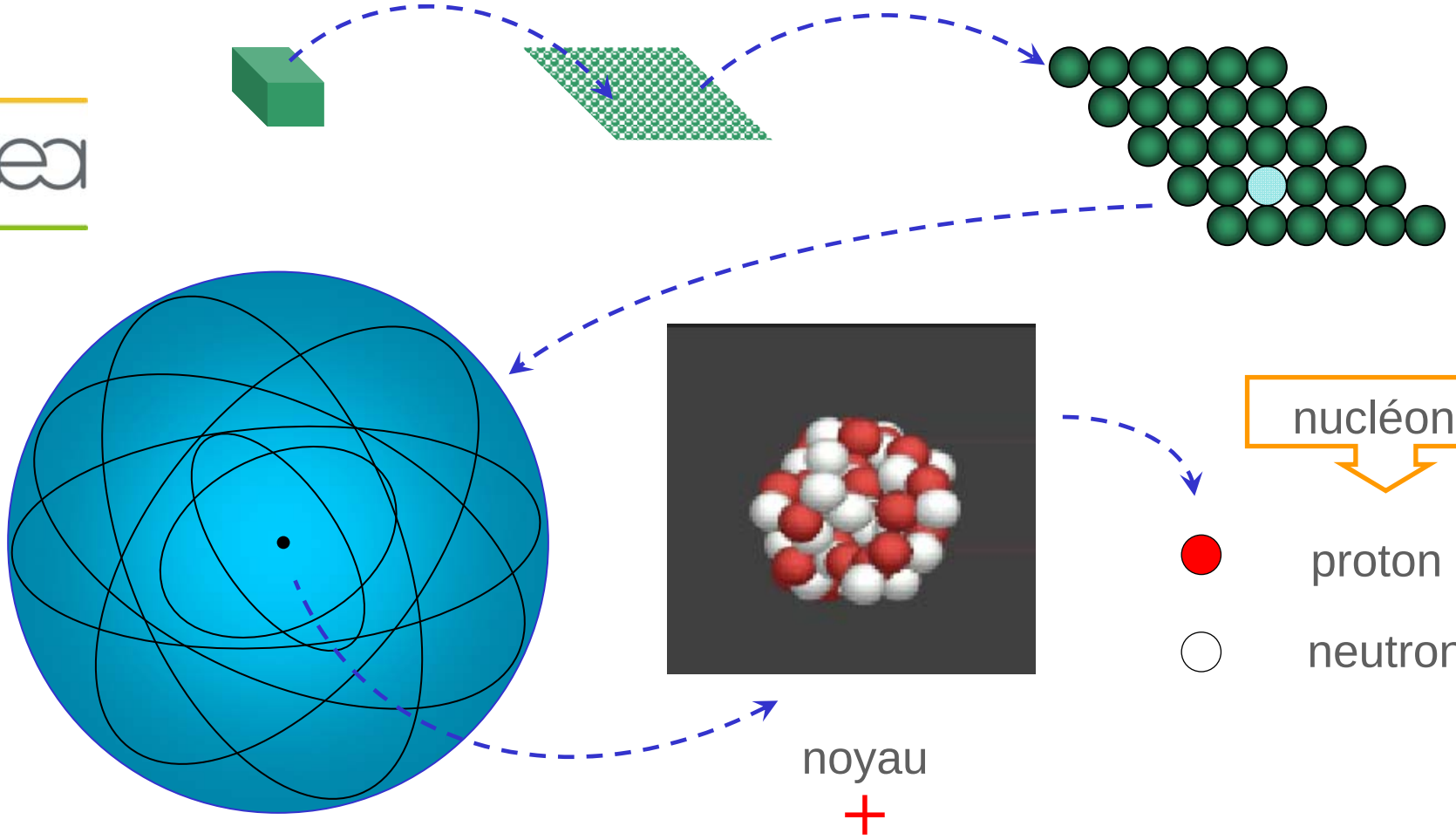
cinétique	10 tonnes à 100 km/h
potentielle	10 tonnes chutant de 40 m
chimique	100 g de carburant
calorifique	fonte de 10 kg de glace
	ébullition de 1.5 kg d'eau
solaire	1 m^2 d'éclairement



fission nucléaire	**10 mg** d'uranium
fusion nucléaire	**5 µg** d'hydrogène
énergie de masse	**30 ng**

20 g *pour toute une vie…*

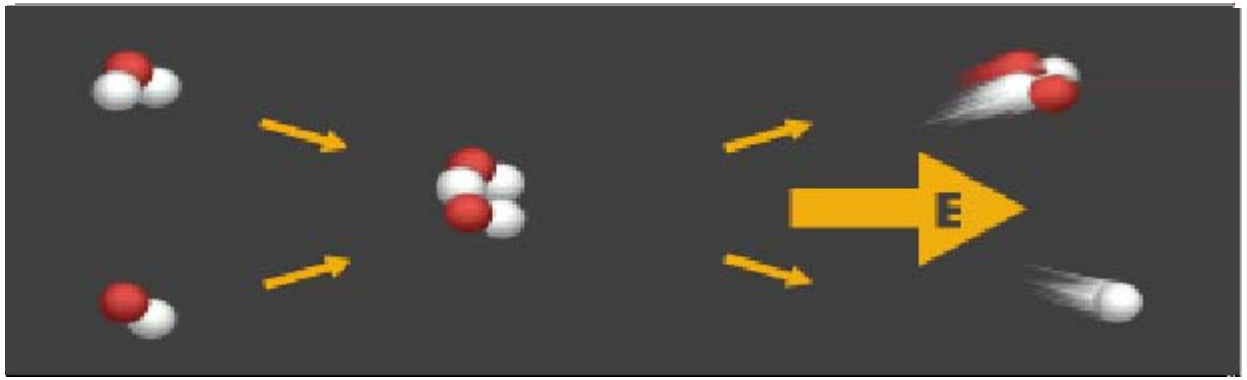
Mais de quoi est constituée cette matière pleine d'énergie ?



*nb de **protons** = nb d'électrons* ⟷ ***élément** chimique*

nb = de protons
*nb ≠ de **neutrons*** ⟷ ***isotope***

Deux types d'énergie nucléaire…



fusion

des noyaux légers

1 H **3** Li

6 C **2** He

… **8** O **7** N

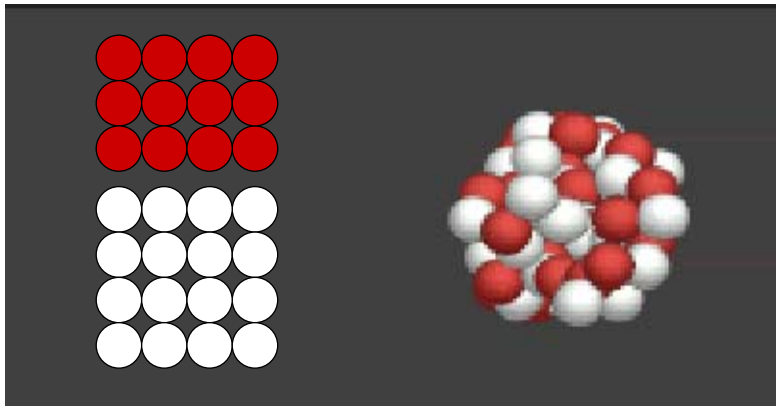
26 Fe

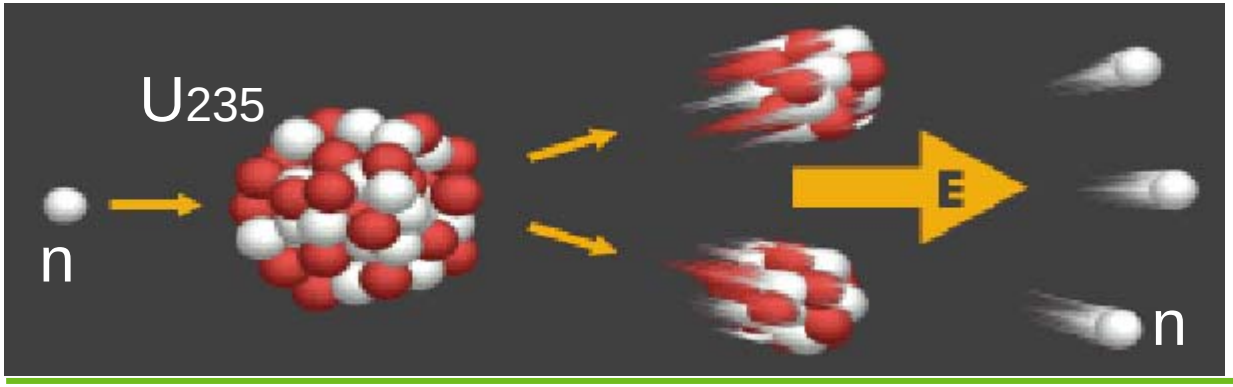
74 W

80 Hg **82** Pb

92 U **116 Uuh**

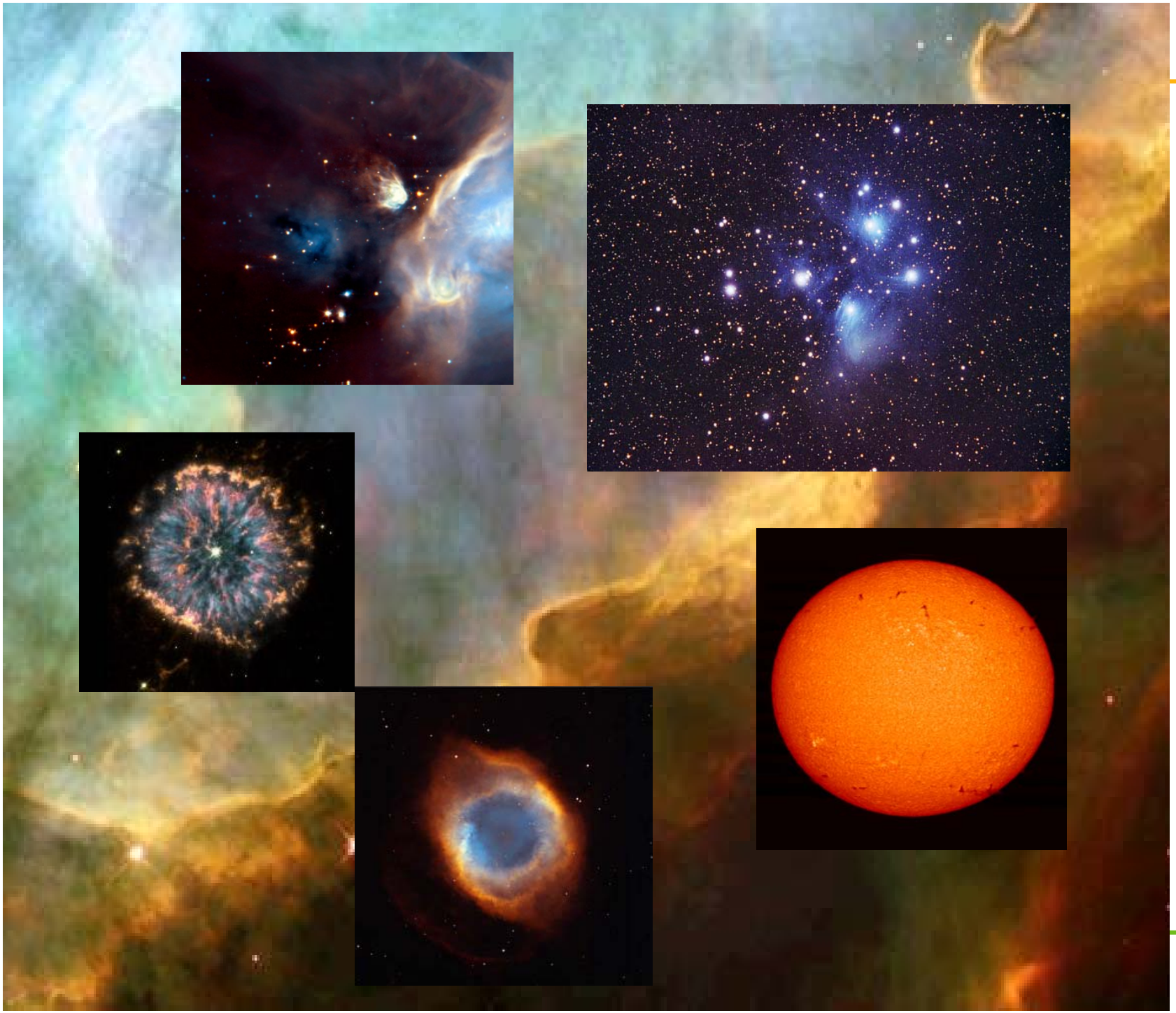
$\Delta E = \Delta m\, c^2$



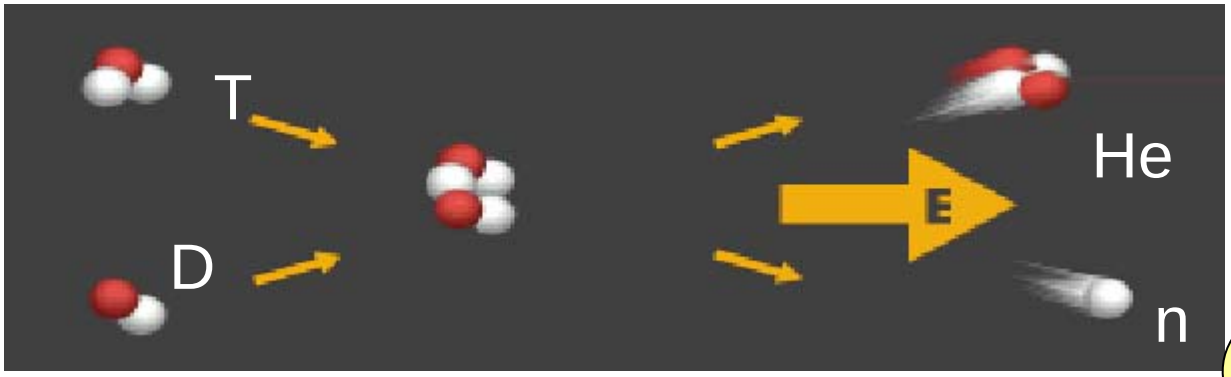


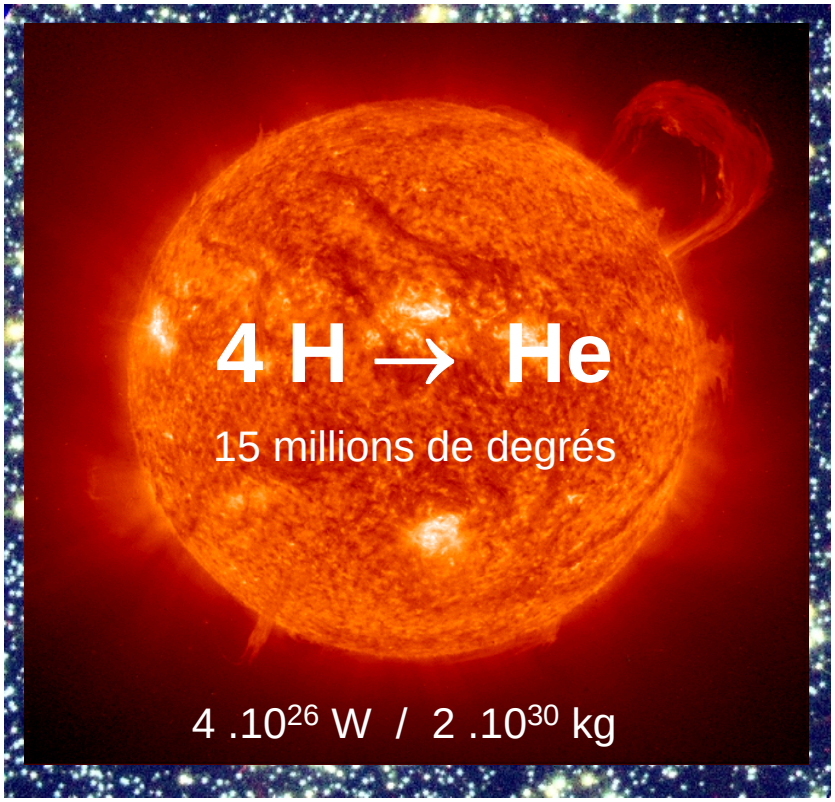
fission

des noyaux lourds

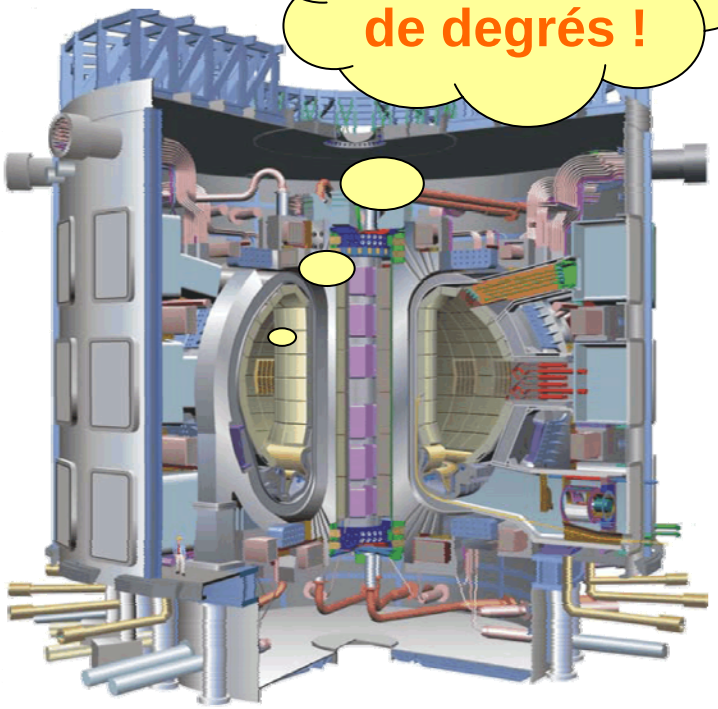


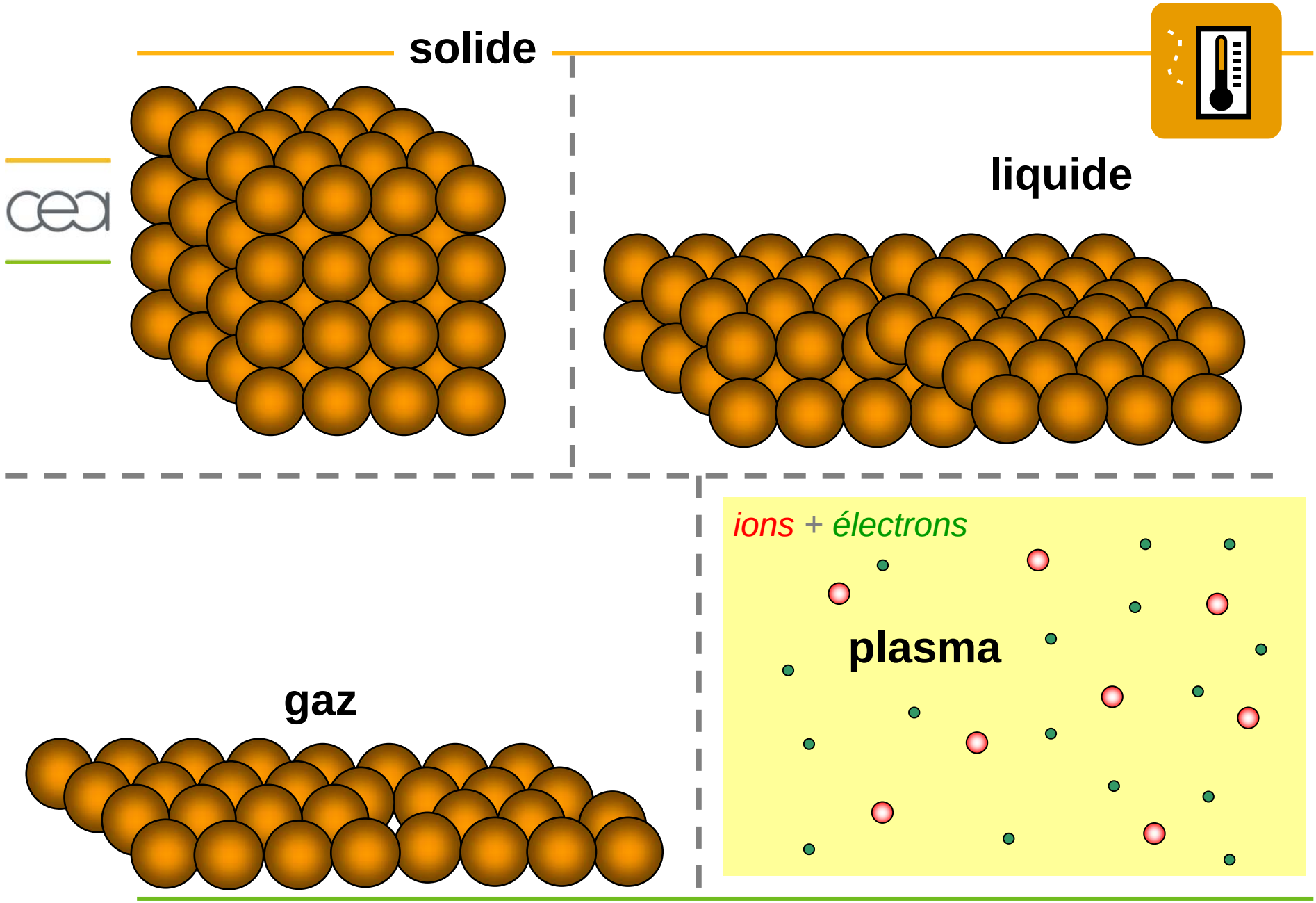
Energie thermo-nucléaire…





> 100 millions de degrés !

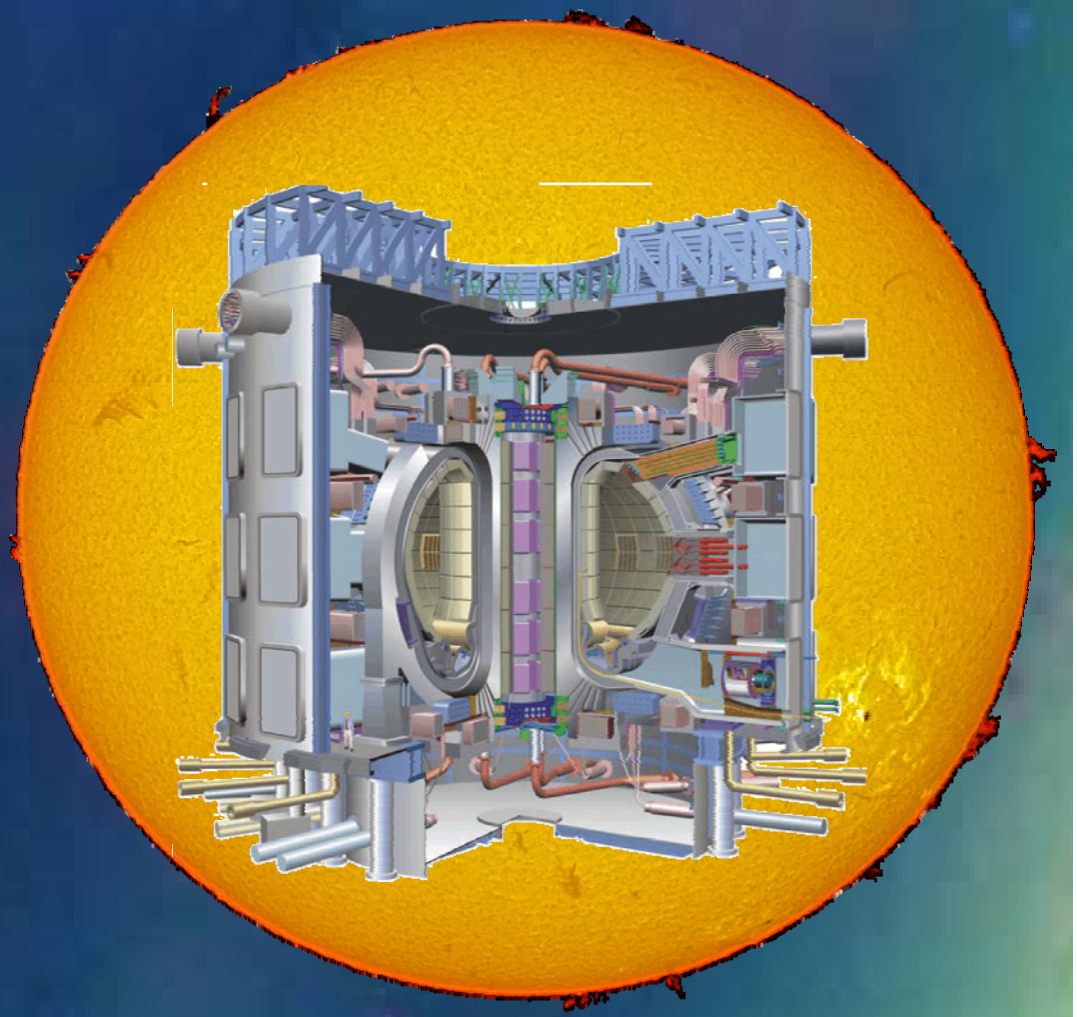



solide
liquide
gaz
ions + électrons
plasma

10.000 °C
1.000 °C
30.000 °C
1 million °C
8.000 °C
6000 °C

La leçon des étoiles…

Éléments légers	H	D – T
Chauffer → plasma	15 10^6 K	100 10^6 K
Confiner	gravitation	magnétique



ALLUMAGE
(« ignition ») si

$$n \times \tau > 10^{20}\ m^{-3}.\ s$$

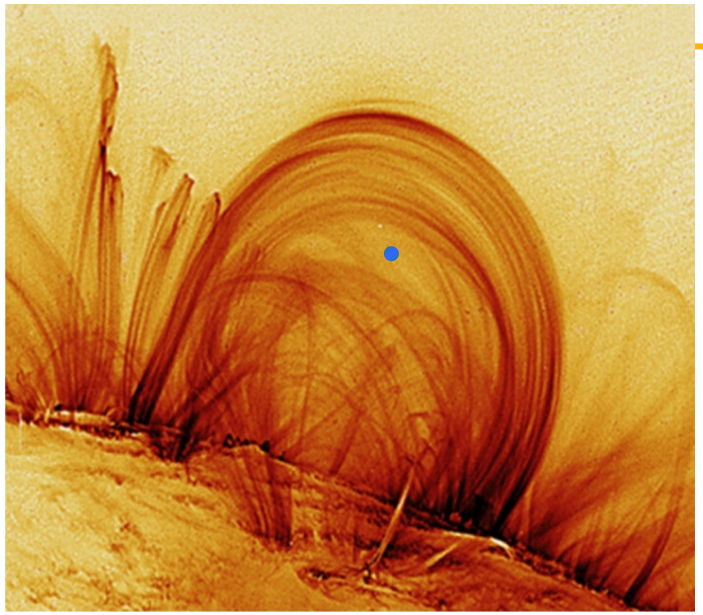
densité du plasma

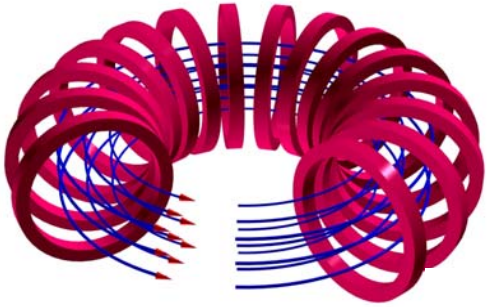
temps typique de refroidissement

n → *10^{20} particules / m3 (< 10^{-5} atm)*

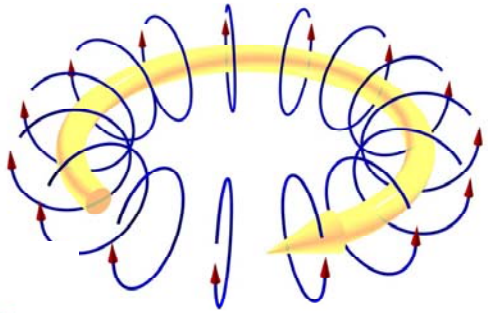
τ → *400 secondes pour ITER*

Confiner…

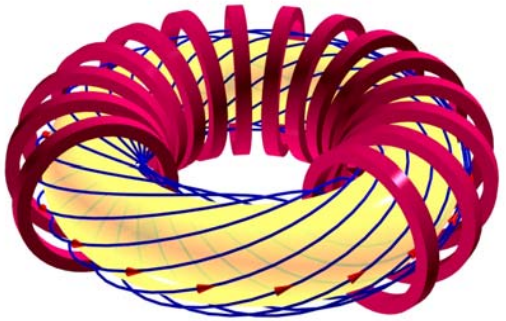




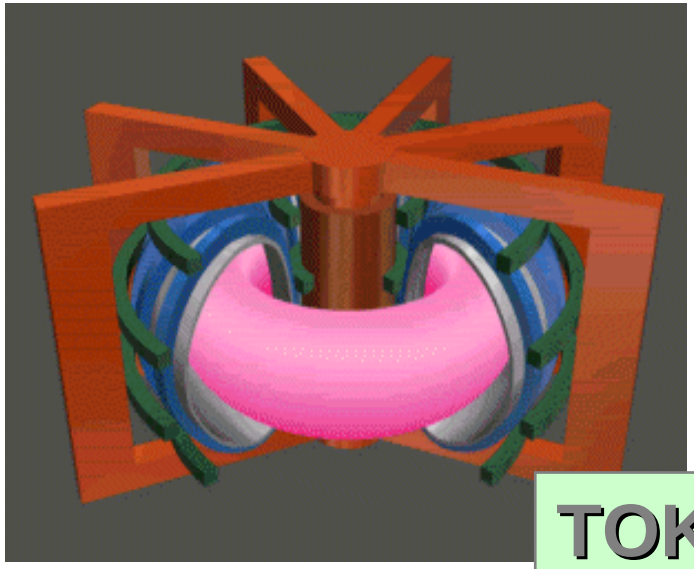
champ
toroïdal 5 T



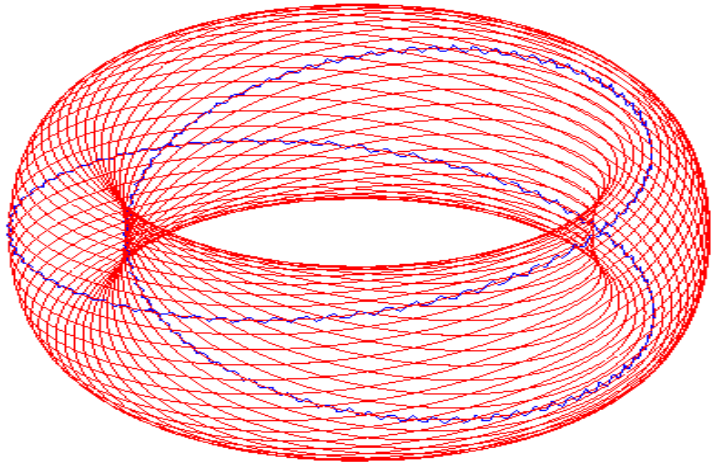
champ poloïdal
→ courant en MA



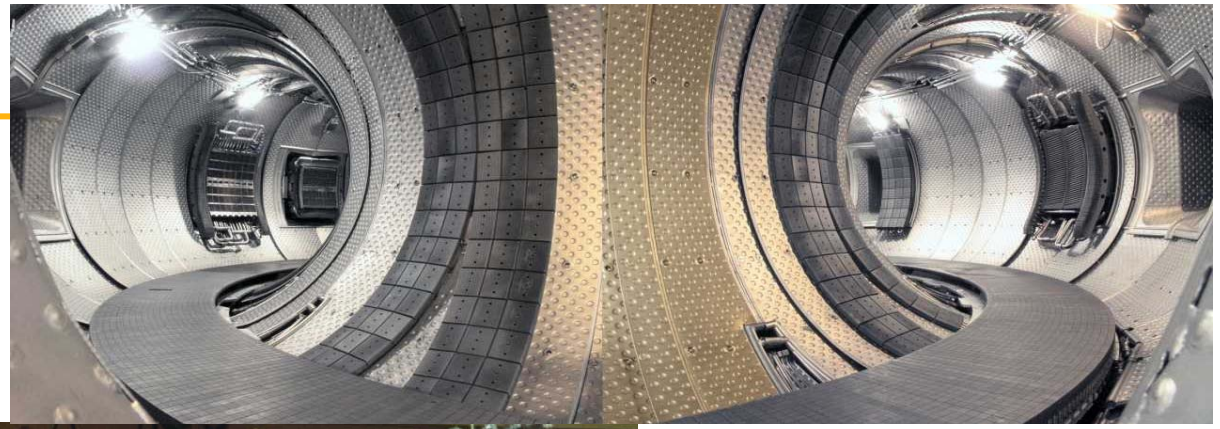
champ total

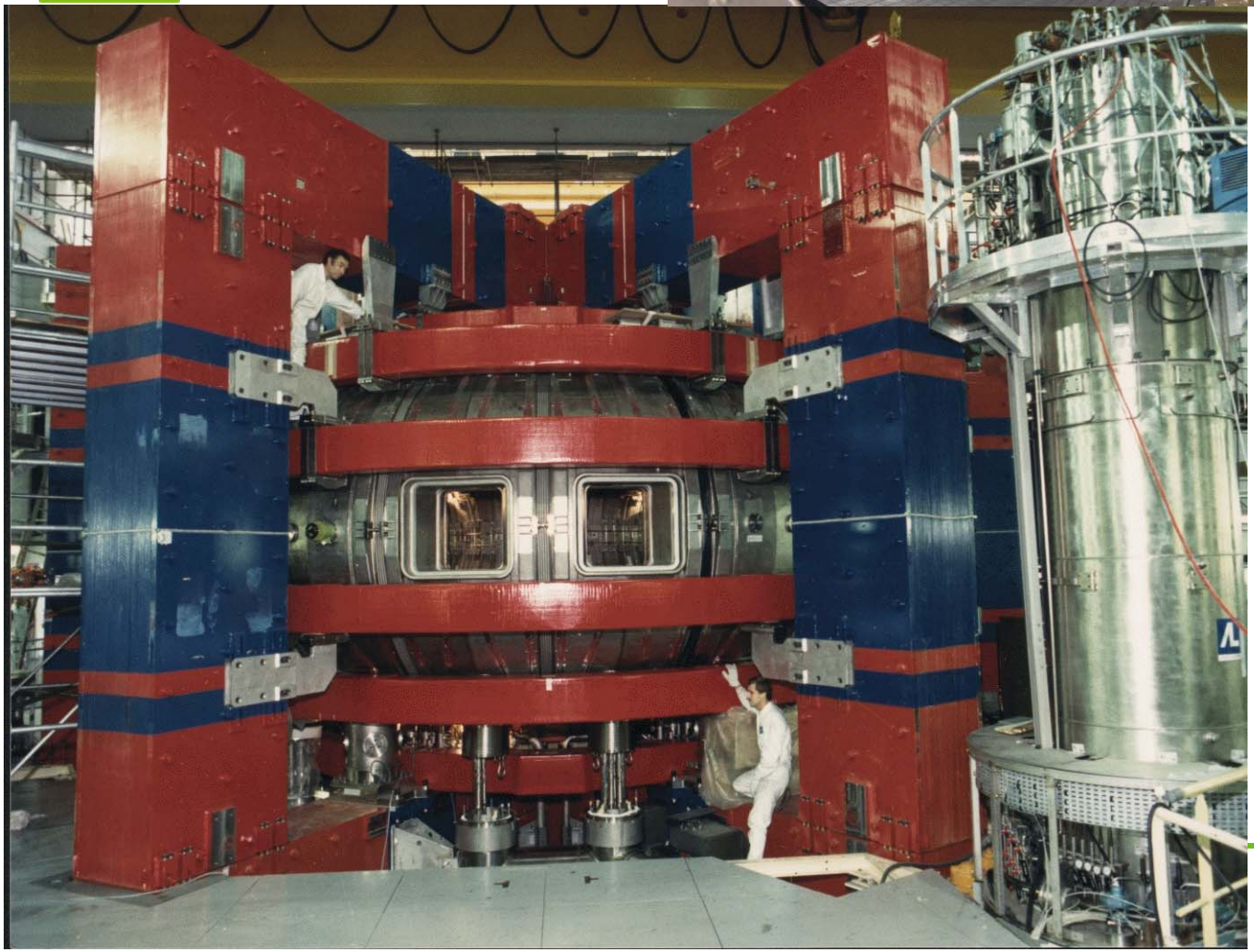


TOKAMAK



TORE-SUPRA
DRFC
Cadarache





1GW électrique

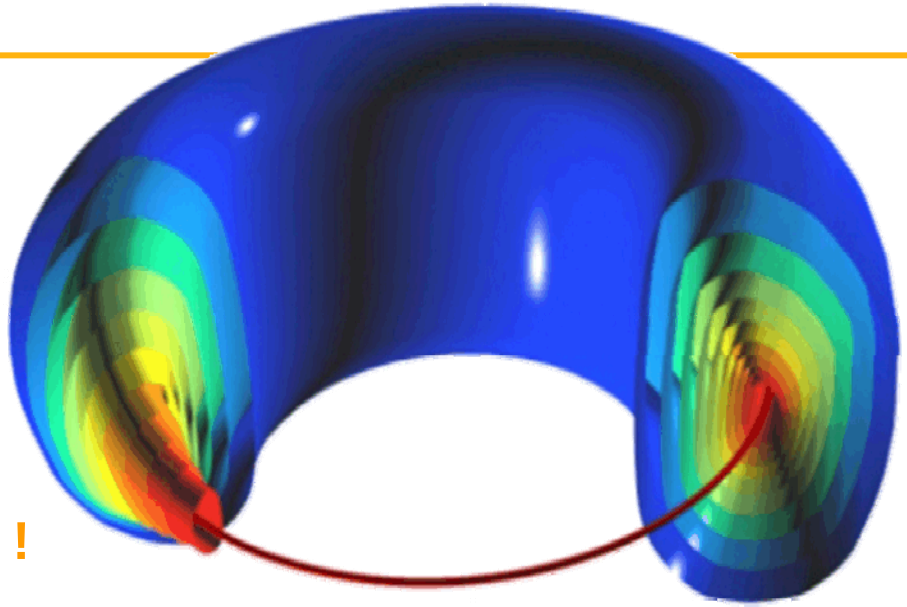
18 bobines

diamètre max : 9m

circuit magnétique
de 830 tonnes

Chauffer le plasma…

La puissance de **fusion** qui chauffe le cœur du plasma par collisions des noyaux He doit suffire à **maintenir** la température à plus de **100 millions de degrés**



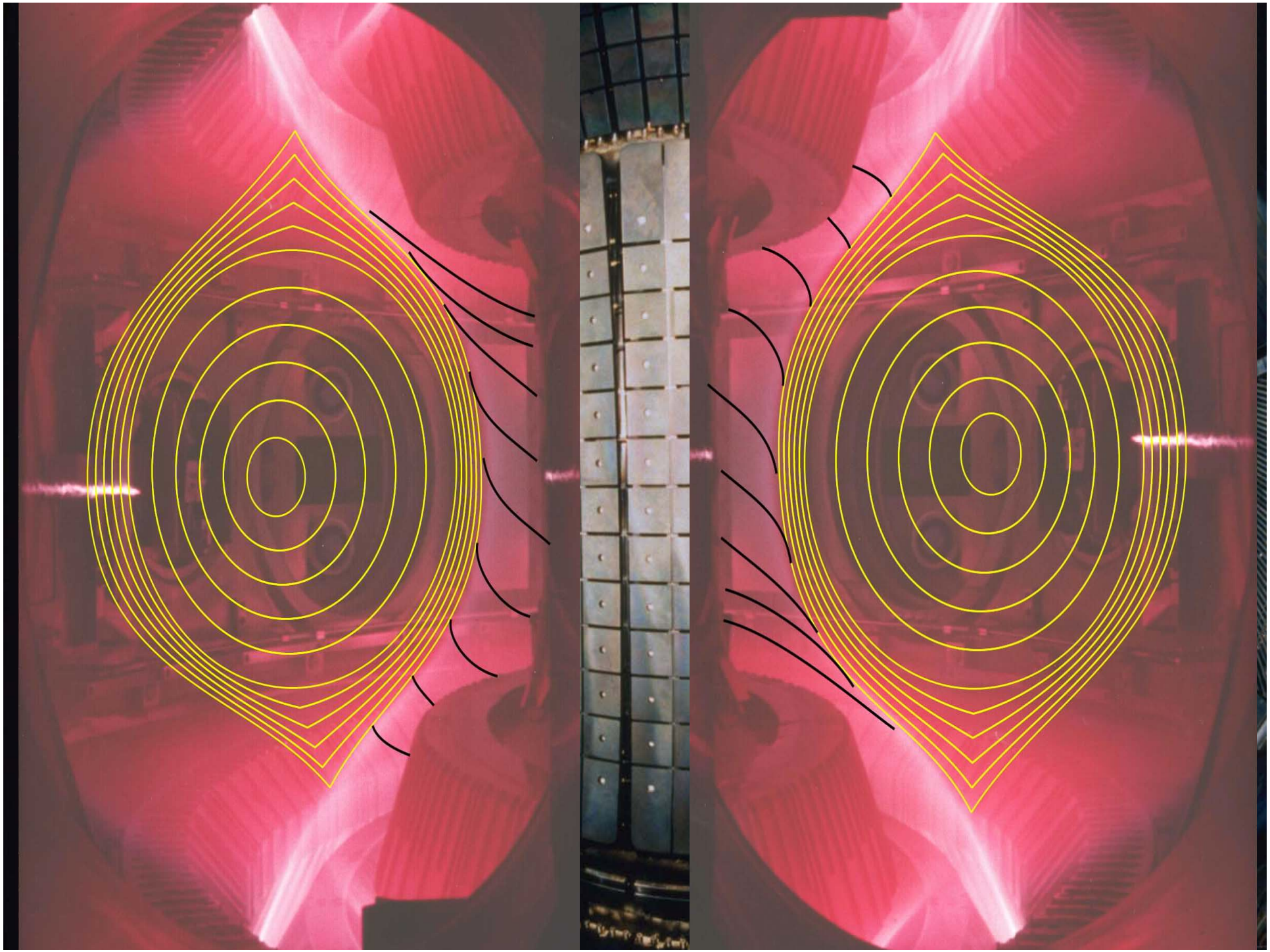
Mais… il faut avoir allumé le feu !

⓪ Bien isoler

❶ Faire circuler du courant → R ↘ quand T↗ : max 10^7 K

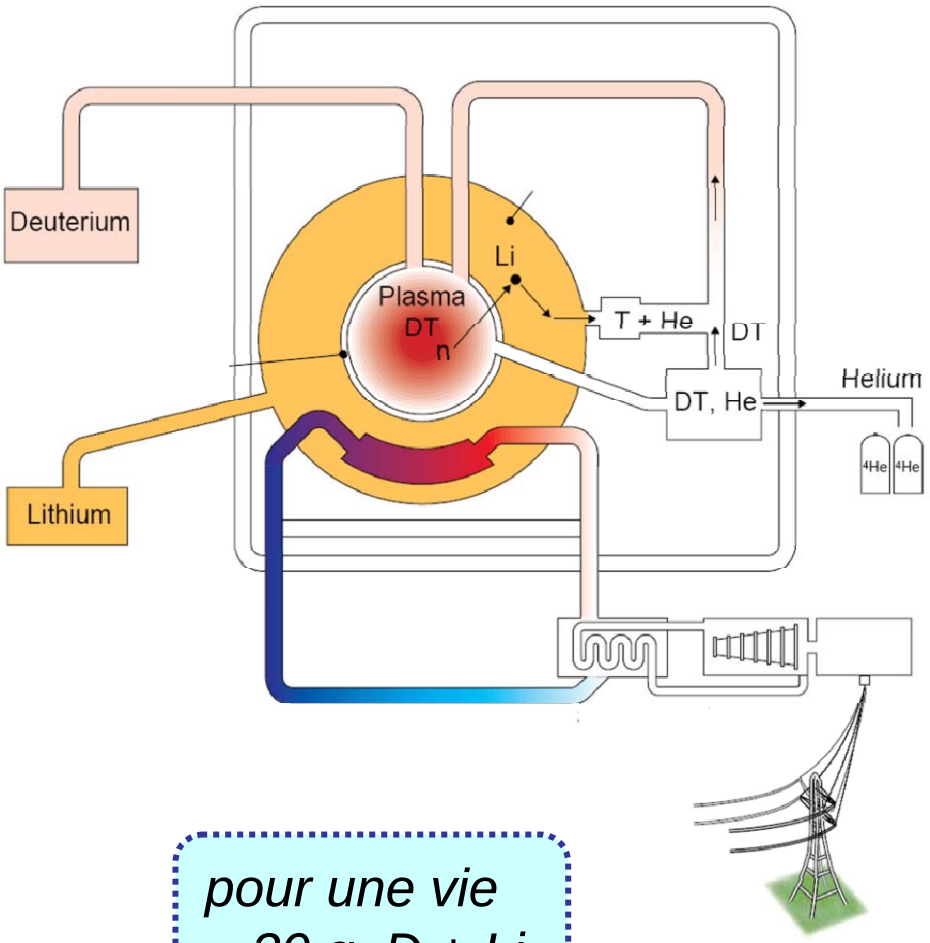
❷ Injecter de l'énergie (et de la matière) → Particules neutres ~ 1 MeV (glaçons de D)

❸ Chauffer au « micro-ondes » → Ondes électromagnétiques / résonances cyclotron (e^- : 100 GHz ; p^+ : 10 - 100 MHz)



2003 → record du monde à Tore-Supra
6 mn 30 s…
…à trois fois la température du centre du soleil

Alimenter en éléments légers



pour une vie
= 30 g D + Li

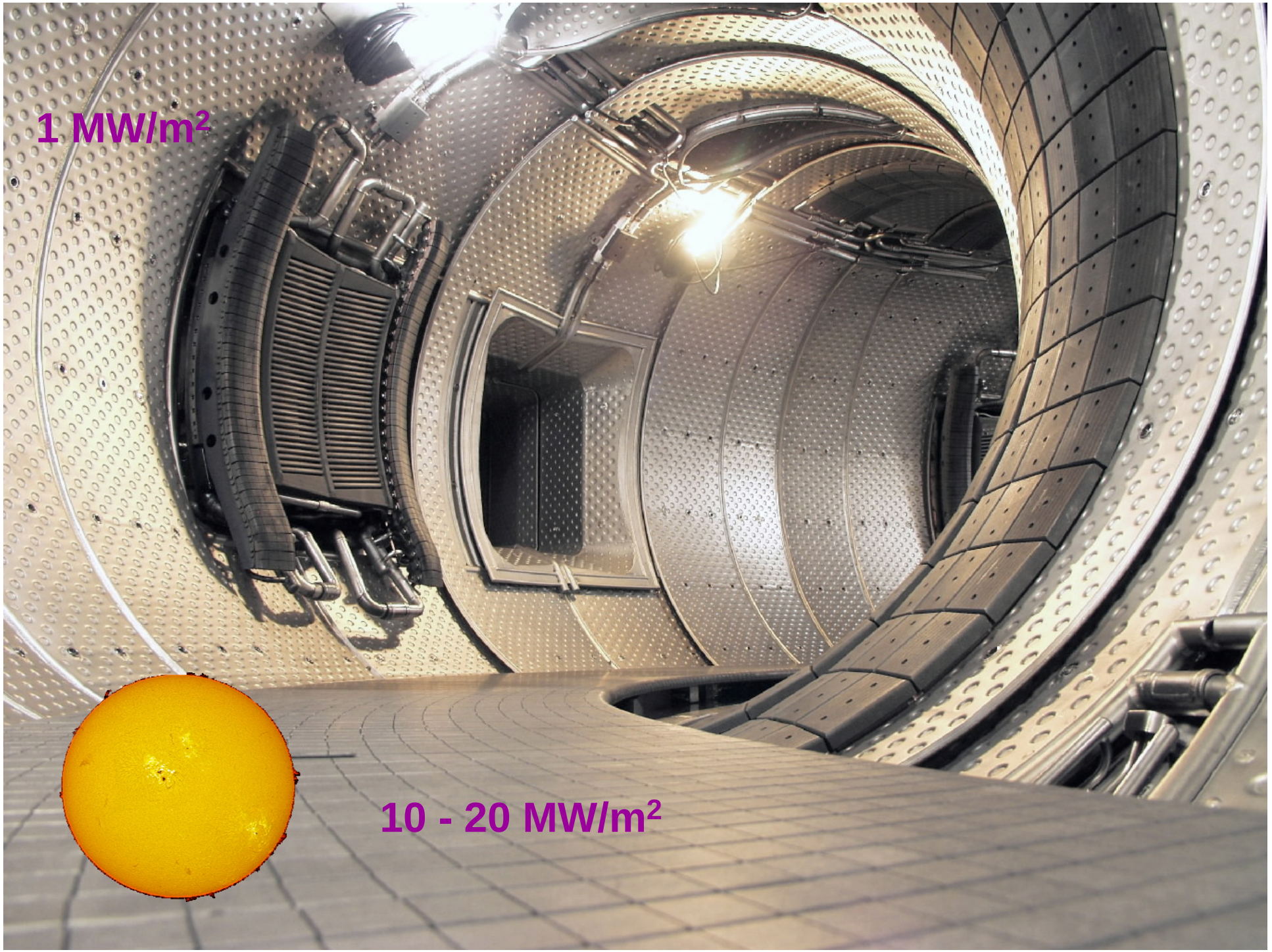
D : 1 atome sur 6700 H,
33 g/t d'eau de mer
→ 10^{10} ans de stock…

T : élément radioactif (demi-vie de 12 ans) n'existant pas dans la nature → à partir du **Li**
(2 g/t de sel de mer – 10^{7} ans)

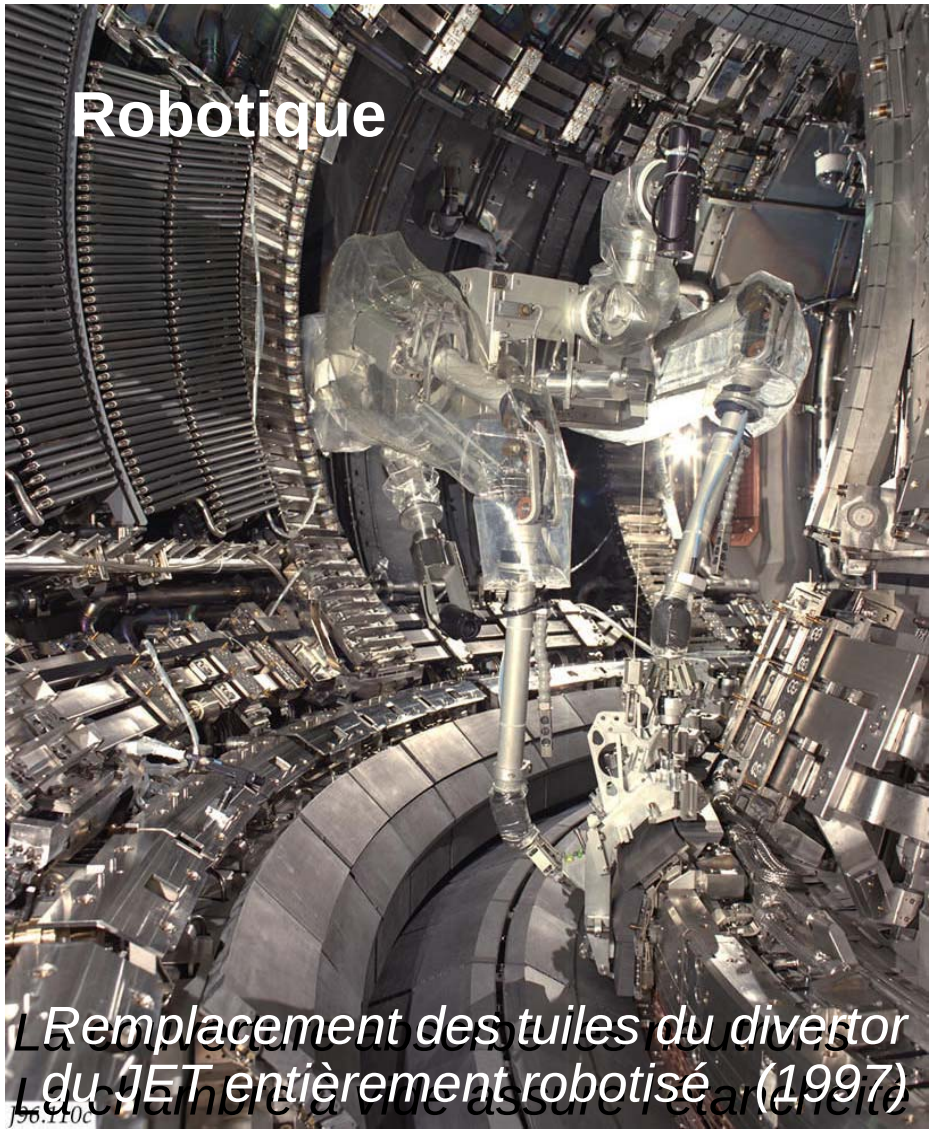
$$D + T \longrightarrow {}^{4}He + n$$

$$^{6}Li + n \longrightarrow {}^{4}He + T$$

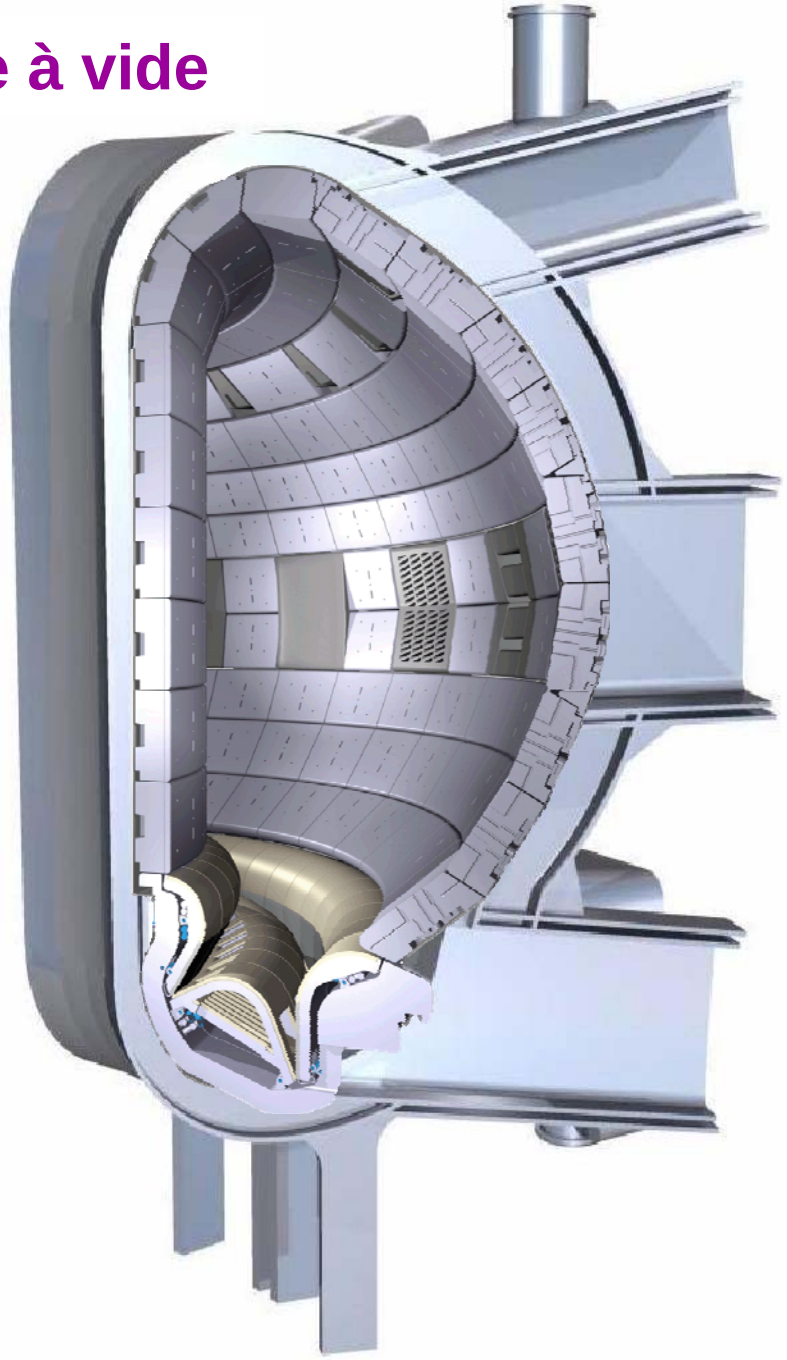
$$D + {}^{6}Li \longrightarrow 2\ {}^{4}He$$

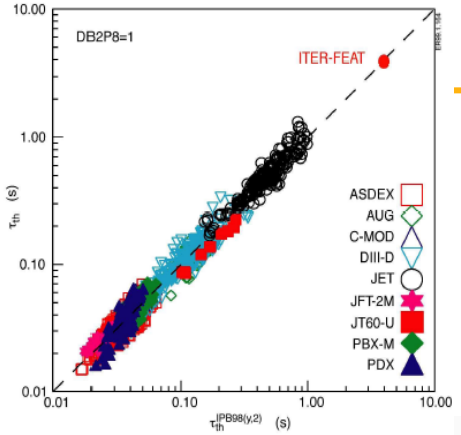

1 MW/m²
10 - 20 MW/m²

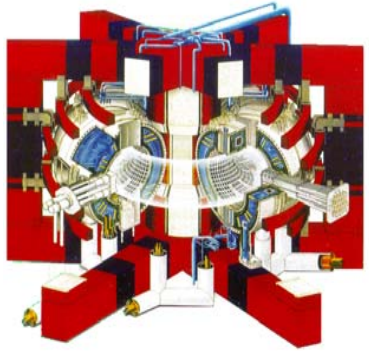
Couverture & chambre à vide

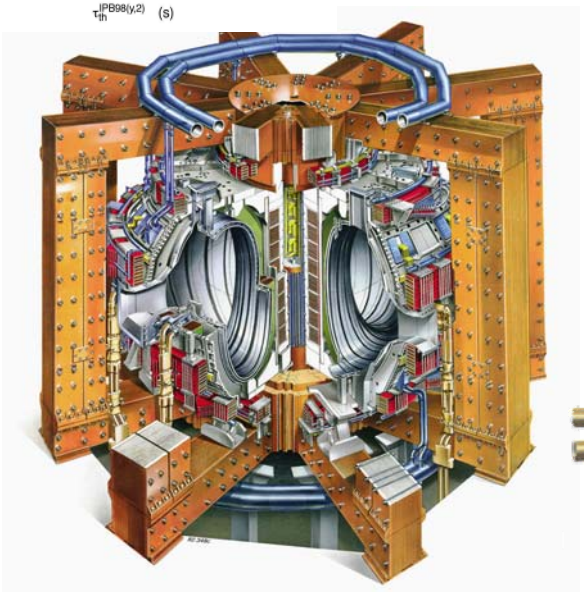


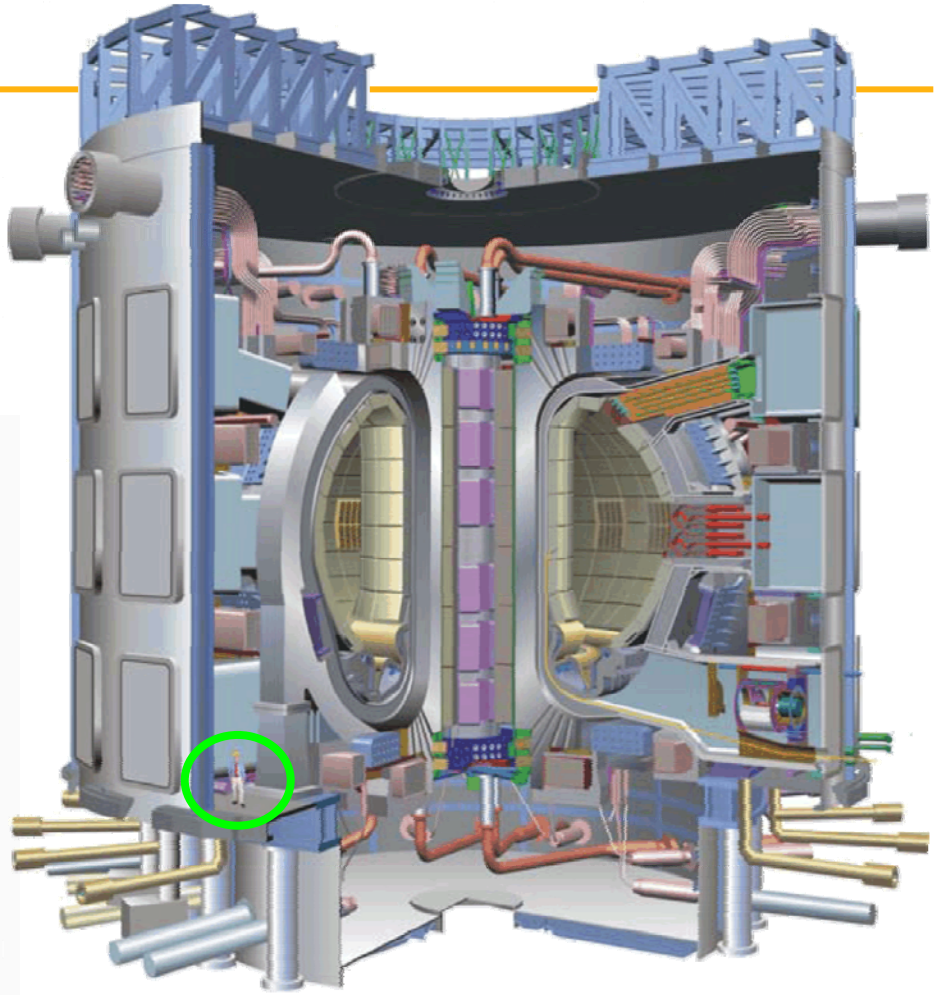
Remplacement des tuiles du divertor du JET entièrement robotisé (1997)











Tore Supra

V_{plasma} 25 m^3
P_{fusion} ~ 0
$P_{chauffage}$ ~ 15 MW

G ~ 0

JET

V_{plasma} 80 m^3
P_{fusion} ~ 16 MW
$P_{chauffage}$ ~ 23 MW

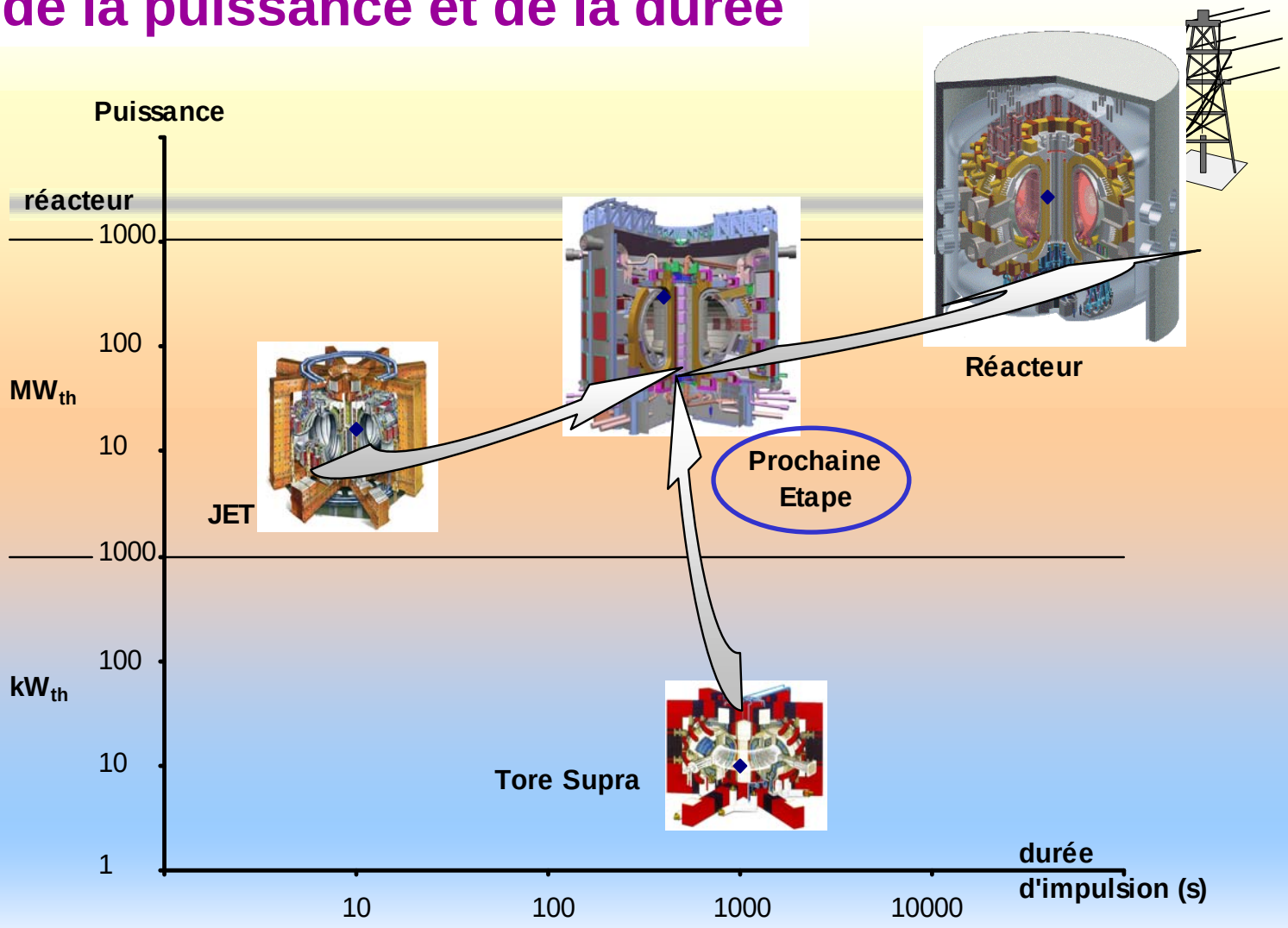
G ~ 1

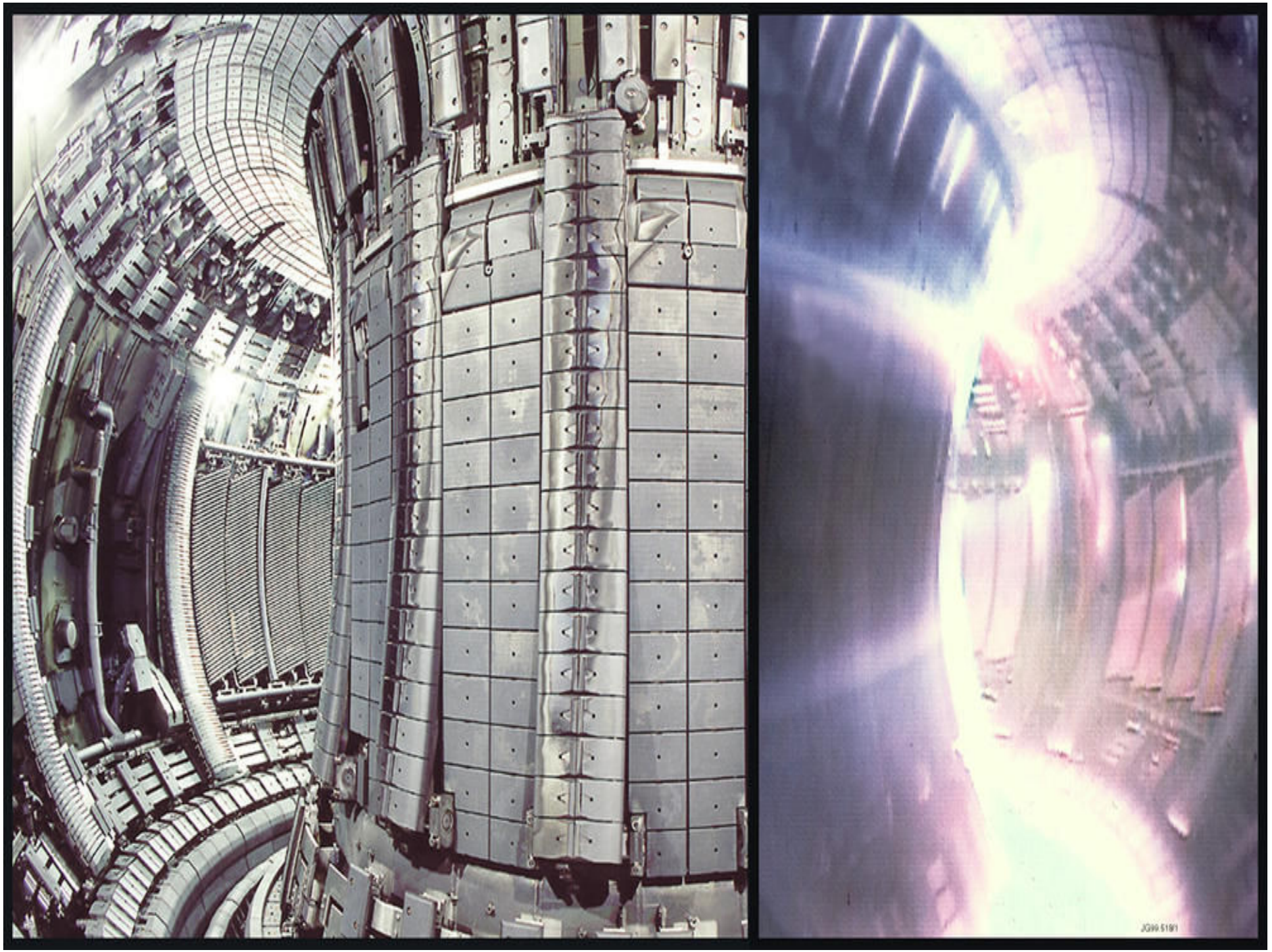
ITER

V_{plasma} 830 m^3
P_{fusion} ~ 500 MW
$P_{chauffage}$ ~ 50 MW

G ~ 10

ITER ou la fusion contrôlée…
de la puissance et de la durée




JG99.51/1